New Directions in Searching for the Dark Universe

Surjeet Rajendran, UC Berkeley
Dark Matter

A New Particle

Non gravitational interactions?

How do we detect them?

Weak effects. Need high precision
Impressive developments in the past two decades

Magnetic Field \( \lesssim 10^{-16} \frac{T}{\sqrt{\text{Hz}}} \)

(Americin magnetometers, atomic magnetometers)

Accelerometers \( \lesssim 10^{-13} \frac{g}{\sqrt{\text{Hz}}} \)

(Atom and optical interferometers)

Rapid technological advancements

Use to detect new physics?
The Dark Matter Landscape

Fit in galaxy

Standard Model scale ~ 100 GeV

One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)
Soon to hit solar neutrino floor

Other Generic Candidates: Axions, Massive Vector Bosons, Dark Blobs

How do we make progress?
Outline

1. Brief Theory Overview
2. Axion Detection with Nuclear Magnetic Resonance
3. Dark Photon Detection with Radios
4. Bosons with Accelerometers
5. Directional Detection of Dark Matter
6. Magnetic Bubble Chambers
7. Conclusions
Bosonic Dark Matter

Photons

\[ \vec{E} = E_0 \cos (\omega t - \omega x) \]

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

\[ a(t) \sim a_0 \cos (m_a t) \]

Spatially uniform, oscillating field

Detect effects of oscillating dark matter field

Correlation length

\[ \sim 1/(m_a v) \]

Coherence Time

\[ \sim 1/(m_a v^2) \]

\[ \sim 1 \text{ s (MHz/m}_a) \]

Today: Random Field

Detect effects of oscillating dark matter field

Resonance possible. \( Q \sim 10^6 \) (set by \( v \sim 10^{-3} \))
What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0
Axions or ultra weak coupling
Many UV theories

Spin 1
Anomaly free
Standard Model couplings

E&M
QCD
Spin
Higgs

Current Searches
QCD
Axion
General Axions
Higgs Portal/Relaxion

Dipole moment
Kinetic Mixing
B-L

Dark Matter \implies a = a_0 \cos (m_a t)
Hz \lesssim m_a \lesssim GHz
Observable Effects
What can the dark matter wind do?
What can a classical field do?

Dark Matter
Oscillating Dark Matter Field (just like oscillating EM field from CMB)

Drive circuit
Spin Precession
Exert Force
Change Fundamental Constants

a/c effect, narrow bandwidth around dark matter mass

SQUID pickup loop
Optical/atomic interferometry
Cosmic Axion Spin Precession Experiment (CASPER)

with

Dmitry Budker
Peter Graham
Micah Ledbetter
Alex Sushkov

CASPER: Axion Effects on Spin

**General Axions**

Neutron in Axion Wind

\[
\left( \frac{\partial \mu_a}{\partial a} N \gamma^\mu \gamma_5 N \right)
\]

\( \vec{v} \)

\[ H_N \supset \frac{a}{f_a} \vec{v}_a \cdot \vec{S}_N \]

Spin rotates about dark matter velocity

Effective time varying magnetic field

\[ B_{eff} \lesssim 10^{-16} \cos (m_a t) \text{ T} \]

Other light dark matter (e.g. dark photons) also induce similar spin precession

**QCD Axion**

Neutron in QCD Axion Dark Matter

\[ \left( \frac{a}{f_a} G \tilde{G} \right) \]

\( \vec{E} \)

QCD axion induces electric dipole moment for neutron and proton

Dipole moment along nuclear spin

Oscillating dipole: \( d \sim 3 \times 10^{-34} \cos (m_a t) \text{ e cm} \)

Apply electric field, spin rotates

Measure Spin Rotation, detect Axion
**CASPEr**

Axion affects physics of nucleus, NMR is sensitive probe

Larmor frequency = axion mass $\rightarrow$ resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

Example materials: LXe, ferroelectric PbTiO$_3$, many others
CASPEr-General Axions

frequency (Hz)

$g_{aNN} \left( \partial_\mu a \right) \bar{N} \gamma^\mu \gamma_5 N$

$10^{-20}$ $10^{-18}$ $10^{-16}$ $10^{-14}$ $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^0$

$10^{-14}$ $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^0$

$10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$

$g_{aNN}$ (GeV$^{-1}$)

mass (eV)

$\sim$ year to scan one decade of frequency

New Force

SN 1987A

ALP DM

Xe

ADMX

He-3

QCD Axion

magnetization noise

$10^{-14}$ $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^0$

$10^{-20}$ $10^{-18}$ $10^{-16}$ $10^{-14}$ $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^0$
CASPER-QCD Axion

\[ d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} \]

Verify signal with spatial coherence of axion field
Dark Photon Detection with a Radio

with

Peter Graham
Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Yue Zhao

arXiv: 1411.7382
Dark Photon Dark Matter

Many theories/vacua have additional, decoupled sectors, new U(1)’s

Natural coupling (dim. 4 operator): \( \mathcal{L} \supset \epsilon F F' \)

mass basis:

\[
\mathcal{L} = -\frac{1}{4} (F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu - e J_{EM}^\mu \left( A_\mu + \epsilon A'_\mu \right)
\]

photon with small mass and suppressed couplings to all charged particles

oscillating \( E' \) field (dark matter) can drive current behind EM shield
Dark Matter Radio Station

oscillating $E'$ field
(dark matter)

Tunable resonant LC circuit
(a radio)
**EXPECTED REACH**

\[ f = \frac{m_{\gamma'}}{2\pi} \]

**Parameters:** volume \( \sim 0.1 \text{ m}^3 \), \( T = 100\text{mK} \), \( Q=10^6 \), 1 year

Surjeet Rajendran, UC Berkeley
Dark Matter Detection with Accelerometers

with

Peter Graham
David Kaplan
Jeremy Mardon
William Terrano
B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current oscillating $E'$ field can accelerate atoms

$$\mathcal{L} = -\frac{1}{4} (F'_{\mu\nu}F'^{\mu\nu}) + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu - g J_{B-L}^\mu A'_\mu$$

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

Force experiments constrain $g < 10^{-21}$

oscillating $E'$ field (dark matter) can accelerate atoms

Force depends on net neutron number - violates equivalence principle. Dark matter exerts time dependent equivalence principle violating force!
The Relaxion

\[ \mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos \frac{\phi}{f} \]

Hierarchy problem solved through cosmic evolution - does not require any new physics at the LHC

\( \phi \) is a light scalar coupled to higgs with small coupling \( g \)

\[ \implies \frac{g\phi}{v} m_q q \bar{q} \]

Dark matter \( \phi \implies \phi = \phi_0 \cos (m_\phi (t - \vec{v} \cdot \vec{x})) \)

Time variation of masses of fundamental particles

\[ \implies \text{force on atoms} \quad \frac{g\nabla \phi}{v} m_q \sim \frac{g m_\phi \vec{v}}{v} m_q \]

Force violates equivalence principle. Time dependent equivalence principle violation!
Detection Options

Measure relative acceleration between different elements/isotopes.

Leverage existing EP violation searches and work done for gravitational wave detection.

Force from dark matter causes torsion balance to rotate.

Measure angle, optical lever arm enhancement.

Differential free fall acceleration.

Stanford Facility
Pulsar Timing Arrays

Pulsars are known to have stable rotation - can be used as clocks

Presently used to search for low frequency (100 nHz) gravitational waves.

Pulsar signal modulates due to gravitational wave passing between earth and the pulsar

Force by dark matter causes relative acceleration between Earth and Pulsar, leading to modulation of signal

Relaxion changes electron mass at location of Earth - changes clock comparison
Projected Sensitivities

Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise
Projected Sensitivities

- Atom interferometry: $10^{-13} \text{g/Hz}^{1/2}$
- Reanalysis
- Next run: $10^{-15} \text{g/Hz}^{1/2}$
- Upgrade
- Static EP tests
- Atomic clock
- LLR
- PTA
- Future: torsion balance

Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise
The Dark Matter Landscape

10^{-43} \text{ GeV} \quad 10^{-22} \text{ eV} \quad 10^{-4} \text{ eV} \quad 100 \text{ eV} \quad 10^2 \text{ GeV} \quad 10^{19} \text{ GeV}

10^{-43} \text{ GeV} \quad 10^{-22} \text{ eV} \quad 10^{-4} \text{ eV} \quad 100 \text{ eV} \quad 10^2 \text{ GeV} \quad 10^{19} \text{ GeV}

Fit in galaxy

Axions, Hidden photons etc. Classical Field Dark Matter

Coherent over T \sim \mu s - 10^6 \text{ years.}

Enough time to build phase \sim (\delta E) T.

ADMX, CASPER, DM-Radio

What about 10^{-4} \text{ eV} - \text{ GeV?}

This Talk

Beyond solar neutrinos?

Close tie to Weak Scale Physics, Thermal Freeze-out

Hard scattering, 10 - 100 keV energy deposition, probing higgs exchange
Directional Detection of Dark Matter with Crystal Defects
(in progress)

with
Alex Sushkov and Nicholas Zobrist
Neutrinos and WIMPs have similar scattering topologies - rare, single particle collision with detector.

Sun produces neutrinos. Irreducible background.

Go beyond next generation?


Challenge: Big Target Mass. Need directional detection at solid state density.
Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm
Collision Aftermath

Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Results of TRIM simulation, 30 keV initial ion

O(200 - 300) vacancies and interstitials, lattice potential ~ 30 eV

Damage cascade well correlated with direction of input ion

Need nano-scale measurement of damage cascade
Nitrogen Vacancy Center in Diamond

Vacancy electron’s transitions can be optically studied

Collect light

Electronic levels sensitive to crystal environment ~ 50 nm scale

~ 1 per (30 nm)$^3$ of NV centers in bulk diamond demonstrated

Nano-scale measurements experimentally demonstrated. Active development of sensors by many groups around the world.

Can this be used for directional detection? What is the effect of the damage cascade on a NV center?

Note: similar phenomenology applies to F-centers of Metal Halides
Damage leads to strain in crystal. Strain shifts transition line

Strain: $\nabla u \propto \frac{1}{r^3} \times \mathcal{O}(100 - 300)$

(Hooke’s Law)

TRIM simulation of damage cascade - calculate strain using Hooke’s law

NV center shift $\sim 100$ kHz @ 30 nm
Natural line width $\sim$ kHz

Single NV center has sensitivity to cascade!
Detector Concept

Large detector, segments of thickness $\sim$ mm

NV center density $\sim$ 1 per (30 nm)$^3$

Conventional WIMP scattering ideas (scintillation, ionization etc.) to localize interesting events

Expect few events/year that could be WIMP or neutrinos

Pull out segments of interest. Conventional schemes localize events to within mm

Micron-scale localization by simply shining light - damaged area will have measurable frequency shifts

For nano-scale resolution, apply external magnetic field gradient - hence need segmentation
Results

Take crystal. Grid of NV centers with density 1 per (30 nm)$^3$

Run ~ 1000 TRIM simulations, get cascade for each. Can grid distinguish direction (including head vs tail)?

More damage in tail vs head used for discrimination. Above 10 keV, efficiency > 80%, false positive < 4%

5 $\sigma$ detection with few events!
Magnetic Bubble Chambers

(in progress)

with
Phil Bunting, Giorgio Gratta, Jeffrey Long and Tom Melia
The Dark Matter Landscape

What about this range?

Coherence time of signal too short for phase measurement to work. Energy deposition too small to be been using conventional WIMP calorimeters

Need amplification of deposited energy (meV - keV)

Challenge: Need large target mass. Rare dark matter event. Requires amplifier stability > years
Consider magnet with all spins aligned

Spins now in metastable excited state with energy
\[ \sim g \mu B \]

Dark Matter collides, deposits heat. Causes meta-stable spin to flip

Spin flip releases stored Zeeman energy (exothermic). Released energy causes other spins to flip, leading to magnetic deflagration (burning) of material.

Amplifies deposited energy. Like a bubble chamber. Is this possible? Stability?
Single Molecular Magnets

Will not happen in a ferromagnet - spins are strongly coupled.


Organo-Metallic complexes. Central metal complex surrounded by organic material.

Weak coupling between adjacent metal complexes - but still large density

Each molecule acts as an independent magnet

Recently discovered systems. Few 100 known examples. Can make large samples. Magnetic deflagration experimentally observed and well studied in Manganese Acetate complexes
Magnetic Deflagration

System well described by 2 level Hamiltonian.
Two states separated by energy barrier.

Turn on magnetic field, metastable state decays to ground state through tunneling

\[ \tau \propto \tau_0 \exp \left( \frac{U_{eff}}{T} \right) \]

Ultra-long lived state at low temperature - localized heating rapidly decreases life-time, decay results in more energy release
Condition for Deflagration

Initially heat region of size $\lambda$ to $T$

Thermal Diffusion, lowers $T$

\[ \tau_D \propto \lambda^2 \]

Spin flips, releases energy, increases $T$

\[ \tau \propto \tau_0 \exp \left( \frac{U_{\text{eff}}}{T} \right) \]

Deflagration occurs as long as we heat a sufficiently large region

$U_{\text{eff}}$ and $\tau_0$ sets the detector threshold. Short $\tau_0$ and small $U_{\text{eff}}$ means tiny energy deposit will sufficiently heat up material to trigger deflagration. Low threshold

Known examples with $\tau_0 \sim 10^{-13}$ s, $U_{\text{eff}} \sim 70$ K, enabling 0.01 eV thresholds
Detector Stability

High energy (> MeV) background from radio-active decays.

Detect MeV events using conventional means. Actual background at low energy very low - forward scattering of Compton events.

Problem: MeV events will constantly set off detector. Reset time vs operation time? Big problem for bubble chambers like COUPP.

Expected background $\sim 1/(m^2 s)$. Initial detector size $\sim (10 \text{ cm})^3$ (kg mass), 1 background event $\sim 100 \text{ s}$.

With precision magnetometers, don’t need entire crystal to flip.

Within $\sim 10 \mu s$, flame $\sim 10 - 100 \mu m$. Visible with SQUID.

Shut off B, turn off fuel. Deflagration stops. Lose $\sim (10 - 100 \mu m)^3$ of volume every 100 s.
Potential Reach

\[ \mathcal{L} = -\frac{1}{4} \left( F_{\mu \nu} F^{\mu \nu} + F'_{\mu \nu} F'^{\mu \nu} \right) + \frac{1}{2} m_{\gamma'}^2 A'_{\mu} A'^{\mu} - e J^\mu_{EM} \left( A_{\mu} + \varepsilon A'_{\mu} \right) \]

Absorption obtained from photoabsorption. Exposure of 1 kg-year.
Conclusions
Poor observational constraints on dark matter

Experiments under development can now search for dark matter particles with mass between $10^{-22}$ eV - $10^{-6}$ eV, using a variety of precision measurement tools.

Explored concepts for WIMP directional detection in solid state densities and single molecular magnets for dark matter in the range $10^{-4}$ eV - GeV.

Need to develop tools to cover full range of possibilities.